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Citation for published version:

Logie, R 2018, 'Human cognition: Common principles and individual variation', *Journal of Applied Research in Memory and Cognition*. <https://doi.org/10.1016/j.jarmac.2018.08.001>

Digital Object Identifier (DOI):

[10.1016/j.jarmac.2018.08.001](https://doi.org/10.1016/j.jarmac.2018.08.001)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Journal of Applied Research in Memory and Cognition

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Logie, R.H. (2018). Human Cognition: Common Principles and Individual Variation. *Journal of Applied Research in Memory and Cognition*.

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Human Cognition: Common Principles and Individual Variation

Robert H Logie
University of Edinburgh, UK

Abstract

A core assumption in cognitive psychology is that common principles govern the functioning of human cognition. I argue that there may be such common principles, but people may use their cognition in different ways to perform the same task in the laboratory and in everyday life. There is a tendency in cognitive psychology research to focus on theories of tasks rather than theories of how the cognitive system might perform those tasks. This raises concerns about widespread reliance in cognitive psychology research on the aggregate data from participant groups, and how applicable theories of tasks are to understanding cognition outside of the laboratory. The concerns are illustrated in four areas of memory research: memory for serial order, mental imagery, cognitive aging, expertise and memory. It is proposed that advances in cognitive theory and applicability would benefit from more detailed exploration of the flexibility of human cognition during task performance.

Keywords Cognitive flexibility; cognitive strategies; theory development; individual variability.

General Audience Summary

Researchers who study human memory often assume that the general principles that govern how memory works are the same for all healthy adults. The contents of memory, that is what we remember, obviously varies from person to person based on their individual experience. However, why we remember some things and not others, how quickly we forget, and why we forget, how we remember the order in which to do things, remember our ATM number, what are the limits on memory, and how our memory ability changes as we grow older are all thought to follow the same general pattern for everyone. So, the researchers look at the average pattern across groups of people and assume that the average pattern reflects how everyone in the group is doing the memory task that is designed for the research. This article claims that what is not always recognized is that there are different ways in which our brains can remember. That is, the brain has a range of memory tools available, and how each memory tool works might be the same for everyone, but people could vary in which combination of memory tools they use when remembering in everyday life or when taking part as volunteers in research studies of memory. For example, when trying to learn and remember words in a new language, some people might say the word over to themselves, others might try to think about whether it sounds like a word they know, and still others might try to visualize what the word looks like and what it means. So, different people might do the same task in very different ways, and if we only look at the average over groups of people, we will miss important insights into the different memory tools that people have available, and how they use them.

Human Cognition: Common Principles and Individual Variation

A core assumption in experimental and individual differences research in cognitive psychology is that there are common principles that govern the functioning and organization of human cognition, and how cognition is implemented within the brain across all healthy adults. An underlying assumption is that evolution would have followed a path to a human cognitive system that enhances the chances of survival of its user. The implication is that there are common principles across all humans for learning, forgetting, encoding, preserving, retrieving, perceiving, controlling action and so on. This view makes perfectly logical sense when we consider that there are common principles governing the function of the heart, the liver, the kidneys, the lungs, the immune system, the endocrine system, thermoregulation, and other outcomes of the evolution of human and non-human mammalian biology. The heart functions in the same way for everyone, even if it varies in size, efficiency and health across individuals, and successful cognition is also important for survival, so why would cognition and associated systems in the brain not function in the same way across people even if they vary in efficiency from one person to another?

In this article, I argue that there may indeed be common principles of cognitive function, but that people may use their cognition in different ways to perform the same task, both in the laboratory and in everyday life. However, there is a tendency in cognitive psychology research to focus on theories of tasks rather than theories of how the cognitive system might perform those tasks. This raises concerns about widespread reliance in cognitive psychology research on the aggregate data from participant groups, and about whether or not theories based on laboratory tasks are applicable to understanding how analogous tasks are performed outside of the laboratory.

Common principles of cognition but different uses of cognition for task performance

The assumption that studies of cognition reveal some common principles that reflect its organization and functioning allows for the development of theoretical models of cognition that attempt to explain a range of phenomena, or make predictions that can be tested in future studies. If it is true that cognition functions in basically the same way for all healthy adults, then, in principle, we should be able to run our experiment on just one individual, and that would be enough to reveal something that would generalise to all other individuals, allowing for variation between and within individuals in the efficiency of the cognitive functions deployed for a specific task and within a given study. To return to the analogy of other organs of the body, investigating the function of one heart in response to different physiological requirements should be enough to understand how all other hearts function, even if there is variability between individuals in how efficiently it can pump blood around the body, and variability within individuals in the frequency and regularity of the pumping action.

A major difficulty with applying the argument above to cognition is that cognitive performance data are noisy because people vary in performance and in the patterns of performance on the tasks they are asked to complete, and not just in terms of the overall performance levels that might vary with overall cognitive efficiency. A given participant might be more or less attentive to the task from trial to trial, might have not fully understood the instructions, might not be motivated to do well, or might have some underlying anomaly such as subtle undetected brain damage. Moreover, cognition is affected by learning and experience that differ from one individual to another. To address this variability in research studies, multiple participants are recruited to be within a specified range of demographics to

maximise homogeneity of the population sample, and data are aggregated across individuals so as to average out individual differences that are assumed to be irrelevant for the phenomena that the experiment is designed to investigate. That is, individual differences in patterns of performance are treated as statistical noise. Therefore, differences and similarities in performance patterns between experimental conditions, across tasks, or between groups that emerge when individual variability is averaged out are treated as representative of all of the participants in the experiment, and are assumed to generalize to the wider population; that is the results from analyzing the aggregate data are thought to reveal common principles of human cognition.

However, there are two major concerns about the assumption of common principles of cognition and the reliance on aggregate data that are explored here. I will elaborate on each of these within the main four sections of the paper, but first give a general summary of each concern to set those later discussions in context.

One concern is that individuals may vary, not only in how well they perform on a task, but how they attempt to perform the task. This concern was raised by Anderson (1978) who noted the logical possibility that for the same set of stimulus inputs and the same set of response outputs, there could be a multitude of intermediate cognitive steps that could be different across different individuals. In other words, the same task could be performed in different ways by different individuals. or by the same individuals on different occasions, and the response patterns might be the same or different, but those response patterns would not necessarily allow us to draw conclusions about the nature of the intermediate cognitive steps. The implication is that for many cognitive tasks, there might be more than one way to achieve a high, or a low level of performance. The same level of performance might be achieved in different ways, or using different strategies. Therefore, considering only the aggregate performance levels could be very misleading regarding the characteristics of cognition.

A second difficulty with the common principles assumption is that any given experiment might reveal only those aspects of cognition that are pushed beyond their capacity by the task demands, and will not reveal cognitive functions that are essential for task performance but that are not required to function at their capacity limits. The latter will remain hidden, and yet may be crucial aspects of the cognitive architecture. In an example experiment, we might measure variation in reading ability across a group of people, and then measure their visual acuity. The correlation between reading ability and visual acuity will be close to zero assuming that there are no participants who have uncorrected impairments of vision. If we just look at the data, then we might conclude that visual acuity is not required for reading. However, if we then blindfold those people, they would be completely unable to read. So, visual acuity is essential for reading, but because it typically contributes well within its capacity limits, its contribution will be invisible in the variability in reading ability. A wide range of aspects of cognition might also be crucial for successful reading but their contribution might be well within their capacity limits, and so they will be invisible in the variability in reading performance. If we want to understand the task of normal reading, this may not be important. If we want to understand the organization of cognition and how it allows us to read, and how reading ability might be impaired, then detecting these invisible cognitive contributions to normal reading will be essential. Their presence will only be detected if they break down in some way, perhaps as a result of brain damage, or if an experiment is designed specifically to detect their contribution.

This concern arises particularly from studies of individual differences, because many cognitive functions that are essential for performing a task will simply not be apparent in the

variability between individuals in their overall task performance scores. The concern may not be important if the goal of the research is to consider only whether variation in performance levels on one task predict or correlate with performance levels on some other task(s). However, if the goal is to reveal something about the organisation of cognition, or of cognitive architecture, and how that architecture supports our everyday activities such as reading, remembering, and interacting with the world, as well as performing laboratory tasks, then ignoring these invisible contributions will mean that important aspects of that cognitive architecture and of our understanding of cognition will be missed.

These two concerns become ever more salient when we start thinking about how findings from research studies might be applicable and applied outside of the laboratory where the tasks that people perform and how they perform them is not as constrained as it is in laboratory experiments. In this article, I will address each of these concerns, drawing on examples of theoretically driven experimental and individual difference studies that have implications for everyday life, namely how people retain serial order, whether visual mental images are functional or epiphenomena, understanding age-related cognitive change, and the role of expertise in memory.

Models of cognition or models of task performance?

Disquiet regarding the first concern above has been expressed for some time. For example, in a study of children's arithmetic Siegler (1987) pointed to the "perils of averaging over strategies." When analysing group average data, he successfully replicated results reported by other researchers. However, on closer examination, he discovered considerable individual variability in the strategies adopted by different children, suggesting that the group effect was largely a statistical artefact. Therefore, basing a theory of children's addition on the average data was very misleading. That is, there may be heterogeneity among participants in how they perform a task, even if the participant sample is homogeneous regarding their age, educational level and socio-economic status. Children may simply have been taught to do arithmetic in different ways, depending on the school they attended, or the educational system of the country in which they live. In this sense, one could argue that any attempt to develop a general model of the cognition associated with simple arithmetic is bound to fail. The mistake is in attempting to develop a model of a task, rather than a model of the cognition that people bring to bear when asked to perform that task. The problem is a general one, and not restricted to mental arithmetic, nor to studies that were carried out 30 years ago.

Whereas there is now broad recognition that performance of mental arithmetic can draw on a range of strategies (e.g., Tiberghien, Notebaert, De Smedt, & Fias, 2018), this does not appear to be the case for many if not most studies of tasks that are designed to investigate common principles of cognition.

Much rarer are examples of studies that have explicitly addressed the second concern about undetected aspects of cognition contributing to task performance. I will explore both this and the first concern in greater depth in each of the four example areas of research discussed in the remainder of this article.

The long-running case of memory for serial order

One major example of considerable effort being devoted to developing a general model of a task that has a long history (e.g., Jacobs, 1887), but remains a contemporary source of debate

(for reviews see Hurlstone & Hitch, 2018; Hurlstone, Hitch & Baddeley, 2014), is the simple yet challenging question of how individuals remember serial order. This is a ubiquitous requirement of everyday life, such as remembering the number associated with our bank card, the combination on our suitcase lock, following instructions (e.g., Jaroslawska, Gathercole, Logie, M., & Holmes, 2016), or learning the sequence of phonemes for a new word (e.g., Gathercole, Willis, Emslie, & Baddeley, 1992; Leclercq & Majerus, 2010). Yet, a generally agreed theory of how serial order is retained in memory remains controversial (e.g., Abrahamse, van Dijck, & Fias, 2017; Ginsburg, Archambeau, van Dijck, Chetail, & Gevers, 2017; Logie, Saito, Morita, Varma, & Norris, 2016; Poirier, Saint-Aubin, Mair, Tehan, & Tolan, 2015).

One possible reason for this continued lack of resolution, could be because there is not just one way in which serial order may be maintained. That is, the major focus of this huge volume of research appears to be to model the task of retaining serial order, rather than how the cognitive system achieves success in doing so. Hurlstone et al. (2014) described several, influential computational models of memory for serial order, each with different assumptions, and each of which has greater or less success in modelling the aggregate data patterns that are observed from groups of healthy participants performing immediate, serial ordered recall, mainly of verbal lists. These models aim to minimise the number of parameters that require to be estimated, so as to follow the general principle of parsimony, that is to account for the data with as few assumptions as possible. This principle avoids the problem that any model could probably fit all of the data patterns from human participants, simply by increasing the number of parameters in the model. The more parameters there are, the more difficult it is to set up tests that might falsify the model. However, maybe we can retain the important principle of falsifiability of a theory (Popper, 1959), yet still consider that the aggregate data from groups of participants might not reflect how cognition achieves retention of serial order. For the sake of argument, let us assume that there are several different ways in which serial order can be retained, and that different individuals select one or other of these methods to do so. We might then reconsider our approach to the problem of serial order by developing falsifiable theories of each method that might be used.

To illustrate the point, one early proposal for how to retain serial order of a list of words is as a simple chain of associations (Ebbinghaus, 1885/1964; Lewandowsky & Murdock, 1989). In a word list, the first word is associated with the second, the second with the third and so on. Reconstructing the order at recall simply involves remembering the first word which acts as a cue for the second word, and so on throughout the list. However, this does not work as a general theory for serial order because during recall, it is not uncommon for people to recall two items from the middle of the list in the reverse order: so called transposition errors. Also, when a word from the middle of the list is forgotten, participants can often remember words from later in the list. If serial order involves a chain, then a break in the chain should disrupt recall of the rest of the list, but this is not what happens.

An alternative view, known as the Primacy Model (Page & Norris, 1998) is that items are retained with different levels of activation, with the first item being the most highly activated, the second being the next most highly activated, and so on with decreasing activation throughout the list. At recall, the most highly activated item is selected and recalled first, and this happens to be the first item in the list. After it is recalled, the activation level drops, and so the second item is selected for recall because it is now the most highly activated item in the list, and so on. This approach has the advantage that it does not depend on a chain of associations. Therefore, when an item is missed, recall can be based solely on the activation levels of the remaining list items. A transposition error is thought to arise from items that are

later in the list having very similar levels of activation, and because there is some noise in the system, there is uncertainty about which has the higher activation level of adjacent items. To be open about inhabiting one of the glasshouses at which I appear to be throwing stones, I am happy to acknowledge that myself and colleagues have used the Primacy Model to study serial order in visual memory (Logie et al., 2016). A third alternative (e.g., Brown, Neath, & Chater, 2007; Burgess & Hitch, 2006) is that there is some learned, general representation of serial order, and each item in the list is linked to a position in that learned representation, known as positional encoding. Recall then involves retrieving each item linked to a particular position in the list, and there is no specific link between the items themselves.

The three brief descriptions above do not comprise a comprehensive list of all of the theories of serial order memory that have been generated (see Hurlstone et al., 2014), but hopefully, the outline descriptions given will illustrate some of the major differences. Each theory has its limitations and strengths when it comes to modelling data from human participants. However, let us now step away from the laboratory studies of remembering word lists, and consider the various examples of how remembering serial order is important outside of the laboratory. If we take the task of learning new vocabulary, the challenge is to remember the sequence of sounds in the correct order. For example, learning a word in the Latin language such as *igitur* (which means *therefore*), requires remembering the sequence *ig-i-tur* that is, an ordered sequence of three sounds. Many words in most languages are this length or shorter, and we know from the large body of research of verbal serial order that most healthy adults have very little difficulty in remembering a sequence of three items. Unfortunately, because most people will perform at ceiling with a sequence of three verbal items, lists of this length are not ideal for experiments in which errors in recall are the primary source of data. This highlights the second major concern mentioned earlier, that there may be aspects of cognition that are crucial for serial order learning within and outside of the laboratory, but because performance is at ceiling with sequences of three items, how this is achieved by the cognitive system will not be evident in experimental studies of memory for serial order. However, learning new words of three syllables does require memory for serial order. Notably, in several studies of memory for serial order with longer lists, participants are presented with items presented as a series of small groups, with a longer time gap between than within groups. For example, a list of nine digits, might be presented as 387-492-716. Typically people can remember longer lists of items when they are presented or are rehearsed in these groups (e.g., Chen & Cowan, 2005; 2009; Estes, 1972; Miller, 1957). One possibility is that participants are then adopting a combination of two methods for retaining serial order, one for the order within each group, for example chaining or decreasing activation across a group, and another for the order of the groups, for example linking each group to its position in the sequence of groups, but any such differences will not be immediately obvious from the data.

The method used for retaining serial order may then depend on the length of the list, or the rate or rhythm of its presentation (e.g., Chen & Cowan, 2009). Thinking about this in terms of the first of my two general concerns, namely participant strategies, with short lists of three or four items, participants might repeat the sequence to themselves (subvocal rehearsal), perhaps relying on chaining that helps guarantee retention of serial order. With slightly longer lists, participants might begin to use subvocal rehearsal and positional encoding. With even longer lists, participants might draw on differential activation levels across the list. The three methods listed here may be increasingly inaccurate for retaining serial order (serial recall), but may support recall of which items were presented (i.e. free recall), even if their order is uncertain. Some evidence for this comes from studies by Ward, Tan, and Grenfell-Essam (2010) who found that participants tend to use serial recall for short lists, even if they are

instructed to use free recall, and tend to use free recall for long lists, even when they are instructed to use serial recall.

There are many other detailed findings and models of serial ordered recall that are beyond the scope of the current paper. Nevertheless, the overview given here should illustrate how a major debate that has lasted many decades in the memory literature might be resolved by considering that more than one solution could be correct, that participants are strategic in which of a range of methods for retaining serial order they deploy in these kinds of experiments, and in everyday life such for learning a foreign language vocabulary. Moreover, there may be aspects of cognition, such as chaining for short lists, that are essential for performance but that are not evident in the aggregate data.

From the argument above, it seems reasonable to ask whether any one theory that is designed to model the errors in recall of lists of seven or more verbal items necessarily is the best model for how people retain a verbal sound sequence long enough to repeat it, and also the best model for how people learn that sequence when learning to extend their vocabulary outside of the laboratory? The number sequence for our ATM card tends to comprise four numbers, and typically is a learned number rather than changing every time we use it. Other kinds of sequences might be remembered very differently. Action sequences typically have a logical order in everyday life: we start the engine on the car before we try to drive away, and we pour the coffee into the cup before we pick up the cup, and then we start to drink the coffee. Any different order would not work, so we tend not to make order errors for action sequences. Making a meal requires steps to be completed in a particular order, actors have to learn their lines in a particular order, and a professional musician has to remember sequences of combinations of notes in a particular order. So again, is a task that involves multiple trials in which we try to remember different random orders of words in an experiment a helpful aid to understanding memory for serial order in everyday life? Exploring different ways in which serial order can be remembered might be more helpful in understanding how this accomplished outside of the laboratory.

Even if we consider that there are general principles for remembering a sequence in order, as suggested above, what if serial order for short lists is accomplished differently than serial order for longer lists? What if *learning* serial order, particularly for short lists involves chaining or differential activation levels across list items, but *retaining* an arbitrary random sequence that changes from trial to trial involves linking each item with its position in the list? To extend this scenario, what if some participants in a given experiment are using chaining and others are using the level of activation of each list item to support their performance? In this last case, the aggregate data from an experiment would only be partially explained by each model, but different models could be applied to different methods used by participants to perform the task of immediate, serial ordered recall. That is, there may indeed be general principles of cognitive functions that support task performance, but it may be an impossible task to develop one correct model for how people use those cognitive functions to perform an immediate serial ordered recall task in an experiment, or in everyday life. However, the observation that temporal grouping helps enhance memory could be the basis for detecting word boundaries when learning a language. For example, to learn the Latin phrase *exempli gratia*, (which means *for the sake of example*, commonly abbreviated to e.g.), we can group the first three verbal sounds *ex-emp-li* (or maybe *ex-em-pli*), have a short gap, and then group the second set of sounds *grat-i-a* (or maybe *gra-tia*), in addition to remembering the serial order of the two groups.

The argument above has the potential to generate hypotheses that could be tested empirically, for example by instructing participants to remember lists in a particular way, or to explore whether different subgroups of participants show different patterns of errors, with each different error pattern best fitted by a different theory (for discussions see Logie et al., 2016; Depoorter & Vandierendonck, 2009). To be clear, I am not questioning the value of computational modelling in studies of serial ordered recall, or of cognitive psychology more generally: quite the contrary. However, I am questioning the assumption that there will eventually be one model of immediate memory for serial order that will account for all of the data. More than one model could reflect how the task can be performed, depending on which cognitive functions are deployed by a participant when trying to maximize their performance on a given task. This would not undermine the principle of parsimony or falsifiability of any one model, but each model or some version of each might fit the data from one subgroup of participants, or a particular experimental manipulation, or an everyday task, but not others.

To illustrate the general argument above with actual data, a study by myself and colleagues (Logie, Della Sala, Laiacina, Chalmers, & Wynn, 1996) investigated the possible use of different strategies across 251 healthy adult participants asked to perform serial order recall of word lists. The lists comprised words that were phonologically different, or were phonologically similar, or were short words, or were long words. In common with many previous studies, we found clear evidence in the group aggregate data of poorer serial recall of verbal lists comprising words that were phonologically similar, or that were multi-syllabic, compared with lists comprising phonologically distinct words, or short words. Although there is a debate about the interpretation of these two findings (for a recent discussion see Guitard, Saint-Aubin, Tehan, & Tolan, 2018), the effects of phonological similarity and word length in immediate serial-ordered recall of word lists have been replicated in a number of studies since they were first observed respectively by Conrad (1964) and by Baddeley, Thomson and Buchanan (1975). However, when Logie et al. (1996) examined performance patterns from individual participants, they discovered that a substantial minority of their sample failed to show an effect of word length, particularly when the word lists were presented visually, and other subgroups failed to show an effect of phonological similarity, even although the effects were statistically highly significant in the aggregate data.

When a subset of the original sample repeated the experiment in Logie et al. (1996), whether or not a participant showed a particular effect on the first test session was a poor predictor of whether or not they showed the same effect on the second test session. Participants were also asked about strategies that they had adopted to remember the word lists, and it turned out that different participants used different strategies to perform the same task, and the strategy that they reported was systematically linked with whether or not they showed a given effect. Participants who reported the use of some form of mental rehearsal of the sounds of the words tended to show the standard effects, whereas participants reporting the use of visual imagery or semantic strategies failed to show effects of phonological similarity and word length. A reasonable, and testable hypothesis is that when participants used subvocal rehearsal, they might have relied on chaining or positional encoding (or both), whereas when they used visual imagery or a semantic strategy, they relied on differential activation levels of items across the list.

A more recent study by Morrison, Rosenbaum, Fair, and Chein (2016) investigated how the task requirements across seven different paradigms for assessing temporary verbal retention affected the strategies reported by participants. They found considerable intra-participant as well as inter-participant variability in reported strategy depending on how verbal short-term retention was tested. However, overall performance levels did not vary systematically with

type of strategy. These results reinforce the argument that participants may use different strategies for performing the same task, so relying solely on the aggregate data could be very misleading. The lack of variability in performance linked with variability in strategy provides evidence for Anderson's (1978) argument that performance patterns do not necessarily reveal how participants are performing any given task.

These kinds of experiments, and a change in approach to consider whether participants differ in how they perform cognitive tasks, would help develop theories of the cognition that supports retention of serial order rather than theories of the tasks that are used to test memory for serial order. In sum, individual variability in data patterns should not always be treated as statistical noise, and could be highly informative for learning vocabulary but also for the wide range of everyday tasks that require remembering a sequence in the correct order.

Individual variability and the phenomenon of mental imagery

I have used the example of memory for serial order above at some length because of the considerable amount of research effort devoted to its study, and because it is a topic to which myself and colleagues have made a small contribution, as well as being an important everyday requirement for successful cognition outside of the laboratory. However, the general argument could be applied to a range of other long-running theoretical debates with everyday implications, that are contemporary, and were never fully resolved. One example is the heated debate from the 1970s through to the mid 1990s about whether the phenomenal experience of visual mental imagery reflects a genuine function of cognition, or is merely an epiphenomenon of how the brain performs tasks that are designed to assess the use of mental imagery. If the latter, then the conscious experience of mental imagery might be like noise outside the factory, but the noise that is experienced does not actually reflect the operation of the factory machinery, and is an artefact of the operation of that machinery.

On one side of this debate were Paivio (e.g., 1971; 1975; 1986; 1991) and Kosslyn (e.g., 1981; 1991; 1994; 2005; Kosslyn, Ball, & Reiser, 1978; Kosslyn, Pinker, Smith, & Schartz, 1979), both strong advocates, with others, for the functional importance of imagery. On the opposite side of the debate were Banks (e.g., 1977; Banks & Flora, 1977) and Pylyshyn (e.g., 1973; 1981), among others who argued that mental images were epiphenomena of conscious experience, and that mental imagery tasks could be performed using propositional coding and tacit knowledge. This debate featured two types of tasks. One of these involved mental comparisons of the size and other properties of two objects or animals, based on presenting the names of the items to be compared. For example, which is larger, a mouse or an elephant, or which is smaller, an ant or a fly? The closer in physical size the pairs of animals or objects are when viewed in the real world, the longer were the response times to make a mental judgement of relative size based on the names. This was known as the symbolic distance effect (Moyer, 1973).

Another task that was widely used to study imagery was mental scanning of objects of learned artificial maps. For example, participants might be asked to imagine the nose of a dog, press a key when they were ready, and then be asked to mentally scan from the nose to the middle of its back or to the tip of its tail, pressing the key again when they had done so. In other experiments, participants were shown a fictional map of an island, with various landmarks shown in different locations. They were expected to learn the map, and then were asked to imagine one of the landmarks, for example, a lighthouse, pressing a key when they had done so. They would then be asked to imagine scanning the image of the map to find another landmark that was close by, or was in a more distant location on the map, and to

press the key when they had mentally scanned to their target. In these experiments, the further apart were the start and end points for mental scanning, the longer were the times for scanning (e.g., Kosslyn et al., 1978).

The imagery interpretation of the findings from these experiments was that the longer mental scanning for longer distances or for comparing objects that are close in physical size provided evidence that mental imagery simulated visual perception: similar differences in response times would be generated when comparing the size of visually presented actual objects that are close in size or very different in size, or when viewing and scanning different distances on a physical map.

In support of the view that the mental comparison and scanning effects were the result of using a propositionally based process based on general knowledge of objects and animals, Banks and Flora (1978), and Potts (1972; 1974) showed symbolic distance effects when comparing the friendliness of animals, or the estimated costs of objects, and argued that these kinds of judgements do not require any form of simulated visual perceptual comparison. They can be accomplished by using tacit knowledge of the characteristics of these items. Very early in this debate, Pylyshyn (1973) argued that while it was generally recognised that not all that is functional in cognition is necessarily available to consciousness, it was (and still is – for discussions see Logie, 2016; Logie & Cowan, 2015) less widely recognised that not all that is available to consciousness is necessarily functional. That is, the experience of mental imagery is our conscious experience of the functioning of cognition, but, like noise outside the factory, what we experience in consciousness does not necessarily give us any insight into how the brain is performing the task it has been set.

Anderson's (1978) comment that there could be a multitude of intermediate cognitive steps between stimulus and response, made explicit the possibility that imagery tasks could be accomplished in different ways, and the same data patterns could arise either from using mental imagery or from using verbal descriptions of spatial layouts. The behavioral data would not necessarily offer a means to distinguish between these alternatives. This would be particularly true if the researchers rely on analyzing aggregate data from groups of participants, without considering that different subgroups might use different strategies for performing the tasks. It is also perfectly possible that a task in which imagery is actually a functional aspect of cognition, could be described in terms of a statistical model (e.g., Logie, 1981), so both could be correct, but from different perspectives.

Kosslyn (2005; Kosslyn et al., 1993) went on to explore the neuroscience of mental imagery, showing that there is activation of primary visual cortex when participants perform mental imagery tasks in functional MRI scans. This was taken as evidence for an overlap between the processes involved in visual perception, and those involved in visual imagery, and hence was interpreted to support the idea that visual imagery is a form of mental visual perception, and therefore a functional aspect of cognition.

A possible resolution to this debate is that whether or not visual imagery is functional in cognition could depend on individual differences in whether or not individuals experience visual mental imagery. This would have important implications for imagery-based techniques to aid or enhance memory in everyday settings that might work for some individuals but not others. For example, the Cognitive Interview (Fisher & Geiselman, 1992) is thought to enhance eyewitness memory, in part by asking people to imagine themselves back at the scene of the crime or incident that they witnessed. However, this has been shown to generate more false memories in older people (e.g. Dodson, Powers, & Lytell, 2015) who might not be

able to use visual imagery as effectively as younger people (e.g. Dror & Kosslyn, 1994). So, in terms of my first concern, a failure to consider individual differences in how people perform tasks can lead to misleading conclusions based on aggregate data, and could have important implications when applying cognitive techniques in real life settings.

A range of subsequent neuroimaging studies has offered objective evidence that there can be considerable variability across individuals in which areas of the brain are activated during performance of visual imagery tasks. For example, a very large number of brain imaging studies have investigated the areas of activation associated with performing the task of mental rotation. In these kinds of tasks, participants may be presented with a pair of pictures of abstract, 3-D objects that look very similar, but the items in each pair are depicted in different angular orientations, with one rotated in the picture plane relative to the other. The task is to decide whether the two items are identical, or if the two items are mirror images of one another (e.g., Shepherd & Metzler, 1971). A typical result is that the larger the angular rotation between the items in each pair, the longer participants take to decide whether or not the two items are the same. Zacks (2008) presented a comprehensive review of the brain imaging studies of this task, and noted that, across the studies that he reviewed, virtually every area of the brain had been implicated in mental rotation. This variability across studies was explained in terms of the specific mental rotation tasks employed and the control conditions for the fMRI contrasts. One alternative possibility is that different participants in the different experiments were performing the same tasks using different cognitive strategies. These could have arisen from subtle differences in the experimental instructions, or they could have reflected variability in the imagery abilities and the strategies used by participants in each study. More detailed considerations of different strategies for performing mental rotation are given in Just and Carpenter (1985), and more recently by Bilge and Taylor (2017).

In order to test the individual differences account of variability in brain imaging patterns for mental rotation, Logie, Pernet, Buonocore, and Della Sala (2011) selected two groups of participants, based on their responses to the Vividness of Visual Imagery Questionnaire (VVIQ - Marks, 1973). One group responded that they regularly experienced vivid visual mental images, and the other group reported little or no experience of visual mental imagery. Each participant was asked to perform a standard mental rotation task with the Shepherd and Metzler (1971) figures while in the MRI scanner. In the behavioral data, both groups showed the typical pattern of longer decision times for larger angles of rotation in the depicted pairs (see Figure 1). Therefore, from the aggregate data, we might assume that all participants were performing the task in the same way, by mentally rotating one item until it was in the same orientation in their mental image of the other item in the pair, and taking longer to do so for larger angles of rotation.

Figure 1 about here

The functional MRI results showed that there was indeed an overlap in the brain areas activated for the two groups when they were performing mental rotation. However, it was equally clear that there were areas of activation that did not overlap. Specifically, high imagers had stronger activations than low imagers over the left and right cingulate gyri, left and right superior frontal gyri, left and right anterior superior temporal gyri/insulae, left and right middle temporal gyri, right inferior frontal gyrus, right parahippocampal gyrus, right cuneus, left midbrain and left lingual gyrus. By contrast, low imagers showed stronger activations than high imagers over the right tuber (cerebellum), left middle occipital/ inferior

temporal gyri, left and right inferior parietal gyri, superior frontal gyri, and middle frontal gyri. That is, low and high imagers were generating different brain activation patterns to perform exactly the same task, and yet both showed the typical behavioral pattern linking response time to the angular difference between items in each pair. This suggests that the two groups were performing the same task and generating the same behavioral data patterns but using different combinations of brain networks to do so.

A key area of application for studies of cognition is how the understanding of healthy cognition can help understand the nature of cognitive problems that arise in individuals who have suffered brain damage. In the context of the cognition of visual imagery, Zeman et al. (2010) described the case of an individual, referred to as MX, who reported sudden loss of the conscious experience of visual imagery, having had the experience of very vivid imagery throughout his life until that point. He also reported that he had used imagery extensively in his profession as a building surveyor from which he had recently retired. Although he performed normally on a wide range of cognitive assessments, and had an IQ well above average, he rated himself as very low on the Vividness of Visual Imagery Questionnaire (Marks, 1973). Figure 2 shows his response times on mental rotation using the Shepherd and Metzler (1971) stimuli. The figure also shows the response times for a group of age-matched, and occupation-matched (surveyors and architects) healthy individuals who showed very little individual variability in data patterns. From the figure, it is clear that his overall response times are very much slower than those for the healthy controls, but he does show a pattern of increasing response time with increasing angle. Using the Crawford and Garthwaite (2004) procedure for comparing slopes between a single case and a group of matched controls, the slopes for these data were found to be significantly different. This suggested that MX was using a different strategy than the control participants to perform the task, and this strategy clearly took longer to accomplish. In a debriefing session, MX reported that he was attempting to match individual blocks and angles perceptually when making his decision, and had no experience of visual imagery, or of mental rotation.

Figure 2 about here

Zeman et al., (2010) then asked MX and a group of matched controls to perform a simple perceptual task and an imaging task in an fMRI study. Using a paradigm originally developed by Ishai, Haxby, and Ungerleider (2002), Zeman et al. presented MX and controls with pictures of famous faces that participants simply had to look at, and with the names of famous people with the instruction to try and imagine the face of the person named. No behavioral data were collected, but it was clear that all participants were motivated to perform the task. Brain activation patterns while viewing famous faces were not significantly different between MX and controls, including expected activity in the fusiform gyrus that is often associated with face processing (e.g., Haxby, Hoffman, & Gobbini, 2000). However, when attempting to imagine what the faces looked like when presented with the names, activation in MX's brain was significantly reduced in a network of posterior regions while activity in frontal regions was increased compared to controls. MX could recognise the faces and names as being of famous people, but appeared to be responding very differently from controls when asked to read the names and to try and generate mental images of faces. Recognizing in studies of healthy individuals that a task that is thought to use mental imagery, such as mental rotation, might be performed differently by people who do not experience mental imagery, gave a basis for interpreting the nature of the impairment from which MX suffered. But there was also a reciprocal benefit from undertaking this kind of research as an application to clinical neuropsychology, given the demonstration by MX that

he was performing mental rotation without the availability of the conscious experience of imagery and using a different network in the brain to compensate for his loss of this ability. This reinforces the argument that healthy participants may also carry out mental imagery tasks without the experience of imagery.

The debate about whether or not the experience of mental imagery reflects functional cognition or is largely an epiphenomenon was never completely resolved, but went out of fashion for a while as researchers involved in the debate retired or moved on to other topics. However, debate continues about whether visual mental representations are functional, not least in the area of number processing using a mentally imaged number line that runs from left to right in numerical order (e.g., Fischer, 2010; Nunez & Fias, 2017), and retention of serial order in the form of a visual image of a mental whiteboard with items imagined in serial order horizontally or vertically (e.g., Abrahamase et al., 2017; Ginsburg et al., 2017; Logie et al., 2016), or imagined in locations on a familiar layout, such as the numeric keypad on a computer or telephone (e.g., Calia, Darling, Havelka, & Allen, 2018; Darling, Allen, & Havelka, 2017). A study of individual differences in how participants attempt to perform tasks that are thought to use imagery could help resolve that debate, with the likely conclusion that both sides of the debate may be correct, and they simply reflect different ways of performing the same tasks, only some of which actually involve the mental experience of imagery, and only in some individuals. Again, the mistake could be to focus on developing theories of the tasks rather than theories of cognition that can support performance of the same task in different ways.

Old and Young Differ in More Than Age

The concern about variation in strategy for the same task also has important implications for our understanding of how cognition changes with age. We know that there is brain atrophy as we age, and although recent evidence suggests that there is neuronal growth throughout the lifespan, it does not keep up with the rate of loss (e.g., Sailor, Schinder, & Liedo, 2017). We also know that there is a decline in cognition with age, and that some of this decline starts in early adulthood (e.g., Park et al., 2002; Welford, 1958). The fact that age-related cognitive decline is so widely reported in the research literature led Perfect and Maylor (2000) to suggest that additional reports of poorer performance in older than in younger adults might make a very limited contribution to our understanding of *how* and *why* cognition changes with age. They suggested that traditional experimental psychology paradigms that explore whether an experimental manipulation or a comparison between groups of participants allows rejection of the null hypothesis, is of limited value in the field of cognitive ageing. They further suggested that predicting poorer cognitive performance by older people is rather less interesting than being able to predict that older people would perform as well as, or even better than younger people on some cognitive tasks. They referred to the latter as “rejecting the dull hypothesis.” That is, if we select any cognitive task, then finding that older people perform more poorly than younger people is hardly groundbreaking. However, showing the kinds of cognition that are insensitive as well as those that are sensitive to increasing age, and understanding why they do or do not change with age might make a more substantial contribution to knowledge.

This view of cognitive ageing research was supported by Salthouse (1996; 1998; 2000; 2015) who has argued that a single model of cognitive aging is much too simplistic, and an exploration of whether there are different age-related trajectories for different cognitive abilities would yield much greater insight. This argument has important implications for the kind of support that people might require in the community, in the home, or when continuing in employment as they get older. If some cognitive abilities are relatively insensitive to age then it may be possible to

ensure that their working or home environment takes advantage of those intact abilities, but provides support for activities that require aspects of cognition that are known to be impaired in old age. That is, community support for older people can be targeted only where and when it is needed, and can recognize the kinds of everyday tasks that an older person is perfectly capable of performing independently (e.g. Gonçalves et al., 2017).

A key related point is that there are individual differences in cognitive performance within groups of older people, as there are individual differences within groups of younger people, highlighted in earlier sections of this paper. Therefore, older people and younger people could differ in several ways that are unrelated to their difference in age. This raises the possibility that group differences observed in research studies might reflect these other individual differences rather than the influence of ageing. As argued earlier, people may adopt different strategies for the same task. On the same argument, older people may adopt different strategies among themselves as well as different strategies from those adopted by younger people. Even although the task and the procedure for its administration are identical for all participants, if older people approach the task in a very different way from the younger group, then arguably the two groups are not performing the same task, and comparing group performance scores could be extremely misleading. It would then be unsafe to attribute group differences to the effects of cognitive decline with age.

The issues above have been raised before. Baltes and Baltes (1990) suggested that increased knowledge and skills acquired over a lifetime can compensate for any age-related decline in cognitive ability. So it is only when the decline is so great that compensation becomes less effective, and there are then more obvious signs of decline in everyday cognition. A similar argument was made by Park and Reuter-Lorenz (2009; Reuter-Lorenz & Park, 2014) who proposed the Scaffolding Theory of Aging and Cognition: that there are compensatory mechanisms at the neural level that arise from a lifetime accumulation of knowledge and skills, thereby reducing the impact on overall cognitive ability from structural and functional decline with age. A related concept in the study of cognitive aging is the notion of “cognitive reserve” (e.g., Alexander et al., 1997; Chapko, McCormack, Black, Staff, & Murray, 2017). This typically refers to apparent preservation of cognitive ability despite the detection of an underlying brain pathology, such as Alzheimer’s disease. The suggestion is that some individuals have superior compensatory mechanisms that can allow for continued normal cognitive function for longer than might be expected until the underlying brain damage becomes too severe for the compensation to be effective. The proposals from Baltes and Baltes (1990) and from Park and Reuter-Lorenz (2009) refer to a form of cognitive reserve that can compensate for underlying brain changes in healthy aging. The implication is that someone who has accumulated a wider range, or greater depth of knowledge and skills over their lifetime will have a cognitive system that is better equipped to withstand the impact of increasing age on their brain structure and function. This offers a clear support for the view that a lifelong broad education and learning of a wide range of knowledge and skills may be beneficial for extending independent living in old age (e.g. Deary, Whalley, & Starr, 2009)

Not only do different cognitive abilities change at different rates across age, different individuals are affected to differing extents as they get older. A well known longitudinal study reported by Wilson et al., (2002) assessed the cognitive abilities of 694 older (mean age=75.9, sd=6.9 when first tested) healthy members of religious groups over a six year period. There were large individual differences in performance on a range of tasks across all ages, and there were different rates of decline across different measures of cognitive ability as well as across individuals, regardless of performance levels during the first testing session.

The authors concluded that age affects different people and different cognitive functions in different ways rather than resulting in some form of global decline.

In a series of studies, Deary and colleagues (e.g., Deary, Batty & Gale, 2008; Gow et al., 2008; Deary et al., 2012; see review in Deary et al., 2009) showed that childhood mental ability measured at age 11 is associated with an individual's level of cognitive ability as well as general state of health and whether individuals were still alive at the age of 79, as well as over the following 13 years. This was based on follow up (from 2000 and continuing) of the Scottish Mental Surveys of 1932 and 1947 when all 11 year olds in Scotland were tested for their general mental ability. These results have shown clearly that ageing is associated with very different changes in ability across different people. Moreover, differences between individuals in childhood can and do affect cognitive performance throughout the lifespan, with many individuals retaining their high levels of childhood mental ability in later life.

The longitudinal study of individuals from the Scottish Mental Surveys and a wide range of other birth cohorts has reinforced the conclusion that individuals are affected by age in different ways, and the focus of those studies is now on identifying what might be the major factors that can account for those differences. However, in line with both of my general concerns, it is often the case in large scale studies of individual differences in mental ability, whether longitudinal or cross sectional, that there is reliance on a global measure of cognitive ability such as IQ, derived from the common variance among a collection of cognitive tests. There tends to be less consideration of the effects of age on different cognitive functions, based on the assumption that the observed common variance across a battery of tests is sufficient. Typically, the residual variance from individual tests is treated as noise in the data set.

Unfortunately, the above approach based on individual differences in common variance across tests misses the possibility that there are multiple different cognitive functions that collectively contribute to overall mental ability. On the same principles it would be possible to derive a single overall measure of biological health based on common variance across individual tests of heart, liver, kidney, respiratory, digestive, endocrine, immune and central nervous system function. This kind of overall measure might be useful for indicating general system integrity and overall health that could be compared between younger and older people. But this too might be seen as testing a dull hypothesis that older people tend to be less healthy than younger people. Such a measure would not be very informative about how each of the individual biological systems contributes to the everyday physical functioning and overall health of an individual across their lives, or why some people are less affected by age than others. Nor would such a global measure of health aid diagnosis of specific pathologies or inform the choice of clinical interventions for a developing illness.

In line with the second general concern for this article, individual variability in performance on some cognitive, or physical task would only reveal the contributions from aspects of human physiology and of human cognition that are stretched to their limits by the task demands. For example, eating a large meal would reveal individual differences in the efficiency and capacity of the digestive system, but would not reveal the contribution of the heart, respiratory, or cognitive system, all of which are essential for successful food consumption, but none of which is likely to be evident in the individual variability observed. Likewise, variability between individuals on a cognitive task will reveal only those aspects of cognition that are stretched to or beyond their capacity limits for task performance, but will not reveal contributions from aspects of cognition that are essential for successful performance, but are not stretched to the limits of their capacity when doing so. So, if we

accept that different cognitive functions can be identified, why would we assume that a derived measure, such as IQ which is based on the common variance across a battery of different tests, would be sufficiently informative about how each of those functions individually contributes to overall cognition, or how those functions are each affected by healthy ageing or by specific neuropathologies?

Some evidence that older people might perform the same tasks differently from younger people came from a large scale study of over 95,000 people between the ages of 8 and 80 who completed a series of tests over the internet (Johnson, Logie, & Brockmole, 2010). As part of a larger internet study (Brockmole & Logie, 2013; Logie & Maylor, 2009; Maylor & Logie, 2010), Johnson et al. asked participants to complete five cognitive tests, focused on recalling digit sequences (digit span), recalling the final words from a series of sentences (working memory span), mental rotation (spatial orientation), reconstruction of color, shape and location combinations of arrays of colored objects, and remembering visual matrix patterns (visual pattern span). The results across the full age range are shown in Figure 3 plotted as Z scores based on the means and standard deviations for 20 year olds on each task.

Figure 3 about here

It is immediately clear from the figure that the changes in scores are dramatically different across adults of different ages. All tests show approximately the same improvement in performance between the ages of 8 and 20, then the tests of visual memory show a decline in early adults, with a significant drop between the ages of 20 and 25 and continue to decline throughout the lifespan. In complete contrast, a test of verbal memory (digit span) improves during early adulthood, and shows no decline until groups over the age of 65. The other two tasks fall in between with noticeable decline beyond the age of 30, and continuing decline thereafter, but at a slower rate than was found for the visual memory tasks. The observation of strikingly different age-related trajectories across these five tasks presents a challenge to the idea that there is a global cognitive ability that underlies age-related cognitive decline. It points instead to a range of different cognitive abilities that change at different rates across age. Note that the increase in the length of the error bars for the older groups simply reflects the fact that there were fewer people in these groups (a few hundred for each age plotted) than there were for the younger groups (tens of thousands for each of the ages plotted between 18 and 50).

The results shown in Figure 3 provide evidence that there is a range of cognitive functions on which individuals can draw when performing everyday and laboratory cognitive tasks. Further, they suggest that some verbal memory abilities are retained in older years much better than are visual memory abilities. This leads on to the question of whether or not younger and older people draw on the same combination of cognitive abilities to perform the same tasks. Johnson et al. (2010) addressed this question by exploring possible changes across age in the patterns of common variance compared with task-specific, or residual variance. The results of this analysis are shown in Figure 4, in which the residual variances from fitted regression lines for each of the five tests are plotted according to different age groups.

Figure 4 about here

What is clear from Figure 4 is that the task-specific variance (residual variance) for digit span increases with age, suggesting that older people are relying more heavily on specific cognitive abilities, perhaps verbal working memory, whereas younger people are showing less task-specific variance, and therefore more common variance for this task. In contrast, for

spatial orientation and visual pattern memory the task-specific variance is much higher in the young than in the old, who rely more on common variance for these tasks. In other words, older people rely more on a specific cognitive ability to perform digit span, and rely more on a general cognitive ability to perform visual memory tasks. The pattern is reversed for visual memory with young people relying more on a specific cognitive ability, perhaps a visual short-term memory system, and older people relying more on general mental ability.

These findings suggest that when given a visual memory task, older people might be using a different approach, or different strategies to maximise their performance than are the young for the same task. In other words, the same task is assessing different cognitive abilities in the younger compared with older participants. Therefore, we cannot assume that any group differences in task performance that we observe between groups of younger and groups of older participants are due to the difference in age, but they might reflect the mechanisms that older people deploy to compensate for any age-related cognitive decline. In line with the theme running through this article, different people may perform tasks in different ways, and so we should be very cautious when drawing conclusions based on aggregate data. This reinforces the view that theory development should focus on understanding the cognitive architecture that supports task performance within and outside of the laboratory rather than attempting to build theories of specific types of laboratory task.

Expertise Matters

An earlier section of this article referred to a widely reported finding that there is a capacity limit of around seven items for recalling a sequence of random numbers in the presented order. That limit shows a modest increase when the items are presented or rehearsed in groups of two or three items. That discussion highlighted that there may be several ways in which people can retain a sequence of items in the correct order. This argument that there are multiple ways to retain serial order gains considerable momentum when we consider the contribution of specific forms of cognitive expertise. Striking examples come from the World Memory Championships¹. The current world record for remembering a sequence of numbers presented aurally at one digit per second is 456 digits, set in 2015 by Lance Tschirhart from the USA. For random words memorised over a period of 5 minutes, the world record is 125 words, and for memorising the order of a pack of 52 playing cards, the record is 13.96 seconds.

In a more controlled laboratory setting, Ericsson, Chase, & Faloon (1980) demonstrated systematically that an individual could be trained to remember digit sequences. Their single participant (Faloon) started the study with a normal digit span, but with extensive training, he gradually increased his span substantially, eventually achieving a span of 80 random digits. However, his general memory ability was not improved in any way, nor was his ability to remember random words or letters. His approach took advantage of an enthusiasm for athletics, and he learned to group short sequences of numbers into meaningful chunks. For example, the sequence 984 could be remembered as 9.84 seconds, or a record time for running 100 metres. He became very proficient at translating number sequences into running times etc., allowing him, after several weeks of intensive training, eventually to dramatically

increase his memory span for digits, but this was specific to digits. More recently, and even more dramatically, Ericsson et al. (2017) have reported a range of memory strategies used by world memory champion Feng Wang who achieved recall of 300 random digits presented at one per second.

These levels of performance go well beyond what is found in a typical laboratory memory experiment, and the individuals concerned learn very effective mnemonic techniques including the use of visual images and stories to make the material more meaningful. That is, these individuals acquire a very rich set of skills that support their world class performance. In a recent conference presentation (Pridmore, 2017), the three times world memory champion, Ben Pridmore from the UK, demonstrated his ability to rapidly learn the order of 52 playing cards in a shuffled pack. He then went on to explain that he had memorized a different bizarre visual image associated with each possible pair of cards. So, the five of clubs followed by the eight of hearts might be associated with the image of a pterodactyl pushing a shopping trolley, and the nine of hearts followed by the king of spades might be a ninja warrior flying a balloon. This has required him to memorize 2652 separate images for all pairwise combinations, including reverse orders for the same pair of cards. To remember the ordering in a pack, he then would make up a story with sequences of these images as he viewed each pair of cards. With the examples above, the sequence five of clubs, eight of hearts, nine of hearts, king of clubs would be imaged as a pterodactyl pushing a shopping trolley in which is a ninja warrior trying to fly a balloon. Visual imagery mnemonics have been known to enhance memory performance since the time of Simonides of Ceos around 2500 years ago (Yates, 1966), and world memory champions have taken these techniques to extreme levels with remarkable results. Such techniques are the basis for many widely advertised systems for improving memory in everyday life.

As with any form of world class expertise, whether it be memorising packs of cards, playing the piano, or carrying out research, many thousands of hours of practice and training are required to master the mnemonic techniques (e.g., Ericsson, 2014; Krampe & Ericsson, 1996), although the interaction between genetics and life experience are also important (e.g. Ullén, Hambrick, & Mosing, 2016). This effective use of mnemonics does raise the stakes in the debate discussed earlier as to whether visual images have a functional role in cognition. It also reinforces the argument that there are multiple ways in which individuals can perform the same task, so modelling a task might tell us very little about cognition.

There are multiple examples of published studies demonstrating superior memory performance within specific domains of expert knowledge and skills. The best known of these involved assessing memory for chess positions. De Groot (1965) asked chess experts to look at the position of pieces from chess games. He then removed the pieces and the experts replaced the pieces in the correct position with no difficulty. People without chess expertise were unable to perform this task successfully. However, when the chess pieces were placed on the board in random positions that would be extremely unlikely during a game of chess, the chess experts showed little advantage in replacing the pieces in the originally viewed positions. That is, the chess experts did not have a superior general memory ability, but they were able to use their knowledge of chess to remember positions from a real game by recognising particular patterns and relationships between the pieces. Clearly, the chess experts were performing the task differently from the non experts.

This effect of domain-specific superior memory appears across a wide range of areas of expertise (for recent reviews see Ericsson, Hoffman, Kozbelt, & Williams, 2018). For example, expertise effects have been reported in memory for maps (Gilhooly, Wood,

Kinnear, & Green, 1988), waiters remembering multiple food orders (Ericsson & Polson, 1988), soccer fans (Morris, Tweedy, and Gruneberg, 1985), and burglars (Logie, Wright, & Decker, 1992). Morris et al. (1985) asked a group of enthusiastic soccer fans to attend the laboratory instead of watching the soccer being played that day. They presented the fans with the scores from the matches that had been played that day, and then asked them to remember the scores that they had seen. Soccer fans could accurately recall the scores for each pair of teams, whereas people who had less interest in soccer could not. However, when all participants were given random pairs of scores for these same teams, the soccer fans were no more accurate than the non experts in soccer. It appeared that, on knowing a given score, the soccer fans immediately made the numbers meaningful by working out how that affected the position of each team in the league, how many points each would now have in the league table, and even guessing who might have scored the goals. They could not use this expert knowledge to retain the random scores.

To illustrate how general is the expertise effect in memory, Logie et al. (1992; Wright, Logie, & Decker, 1995) studied the effect in groups of residential burglars. The researchers showed photographs of houses to individuals who had been charged with residential burglary, and who were being held on remand pending a trial. Many had been convicted of previous, similar offences. The photographs were also shown to a number of police officers and home owners. For each photograph the participant was asked to judge whether or not the house, as shown in the photograph would, or would not be attractive to a burglar. In some of the photographs, the house was shown with a window open, or there was a car in the driveway, or a beware-of-dog sign on the door, or a hedge out front. After viewing the photographs, the burglary participants were asked about their offending history, their motivations for breaking into houses, and what factors might deter them such as sentencing, possible financial gain, risk of being caught, and ease of entry. The other participants were asked analogous questions from their own perspective. All participants were all then given a surprise recognition memory test in which they were shown photographs of the same houses but for some photographs crucial details had been changed. For example, a previously open window was now shown closed, there was now no car in the driveway, or the beware-of-dog sign had been removed. Participants were asked to decide whether or not each photograph had been changed. The burglary participants achieved 78% correct performance, the police achieved 68%, and the homeowners were at chance, scoring 47%. The pattern across groups of participants was reversed when changes in the photographs affected the general appearance of the door, or features in the garden that would be of more interest to homeowners. In other words, burglars also have a form of expertise related to their activities that gives them a benefit when remembering details that are related to their specific expertise. That is, the groups were encoding the photographs and performing the task in very different ways.

Conclusion

This article explored the assumption that there are common principles of human cognition that are relevant for human memory both in laboratory tasks and everyday life, but that a full understanding of those principles is constrained by (a) too much reliance on developing theories of tasks rather than theories of cognition that can be brought to bear during task performance both within and outside the laboratory, and (b) lack of consideration of aspects of cognition that are essential for task performance but that do not contribute to variance in data. Both constraints to understanding result from reliance on patterns of data that are aggregated across participants without regard to whether different individuals might perform the given tasks in different ways. These constraints are illustrated by discussing four key

topics in the study of cognition: (i) remembering serial order, (ii) the use of mental images, (iii) cognitive change with age, and (iv) the impact of expertise.

Failure to consider that different people might perform the same task in different ways, or that the same people might use different approaches to the same task on different occasions can result in very misleading conclusions about the nature of the underlying cognition. This has serious implications if such conclusions are then the basis for applications outside of the laboratory. Moreover, it may fuel a never ending debate between research groups as to which single theory or model can best account for the aggregate data patterns observed. Here, it is argued that more than one theory may be correct, but each might be relevant for different ways in which the architecture and organization of cognition can support task performance. One approach to addressing these issues involves first accepting the possibility that there is more than one way in which a task may be performed, and that the goal is to understand the organization of cognition, not to develop models of tasks. Experimental methods are ideally suited to exploring this, but as a standard procedure, researchers could consider whether there are subgroups of participants that systematically, and reliably do not show the aggregate data pattern rather than treating their data as statistical noise. This could be coupled with a detailed task analysis of what would be required to perform a given task, including aspects of cognition that do not contribute to performance variance across trials or participants. While designing experiments, researchers could more carefully consider the real world relevance of what they are doing, and by attempting to apply some laboratory findings to real world problems, there can then be benefits to understanding of cognition and generalisability of theories of cognition.

The general conclusion is that cognition comprises a set of mental tools and strategies that can be applied flexibly when confronted by task demands in the laboratory or in everyday life. This conclusion hopefully will encourage a research focus on understanding the nature of those mental tools and how they act together in different ways to meet task demands. It might also encourage research groups who are on opposite sides of theoretical debates to conduct open-minded joint research that could lead to new and more integrated theories of cognition that are less concerned with specific cognitive tasks, and are more applicable to understanding cognition outside of the laboratory where individual differences in how everyday cognitive tasks are performed may be even more prevalent than they are when cognition is studied in laboratory settings.

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Figure Captions

Figure 1. Response times for high and low imagers for different angles of rotation on a mental rotation task performed in an MRI scanner (Reproduced from Logie, Pernet, Buonocore & Della Sala, 2011)

Figure 2. Response times for single individual MX, and a group of age and occupation-matched healthy control participants on a mental rotation task.

Figure 3. Z Scores standardized on 20 year olds for five measures of different working memory functions collected via the internet from 111,188 participants aged 8 to 80 years.

Figure 4. Residual variances from fitted regression lines for 95,199 participants across five working memory tests and 14 age groups. Age Group 1=18-20 years, Group 14=80-90 years. Other groups are in 5-year age bands, e.g. Group 2=21-26 years, Group 3=26-30 years and so on to Group 13=75-79 years. Figure reproduced from Johnson, Logie and Brockmole (2010).

Figure1

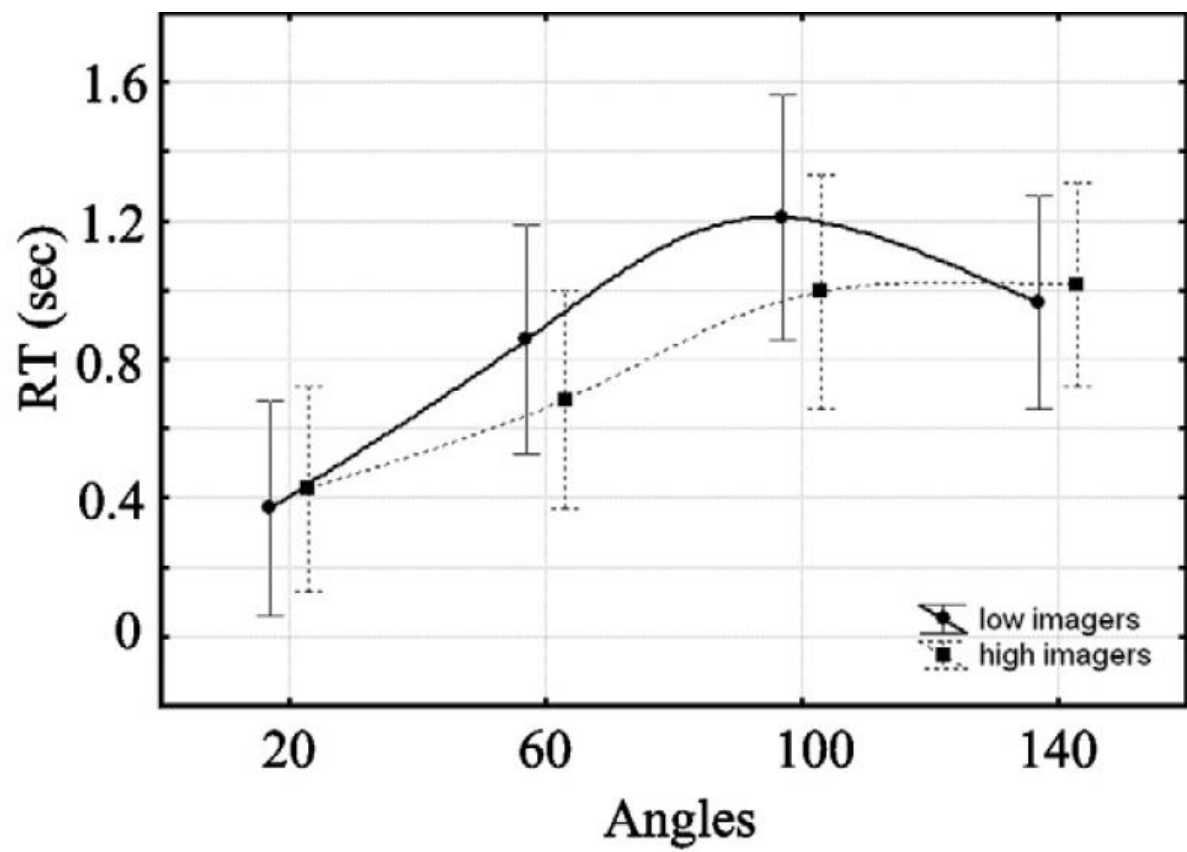


Figure 2

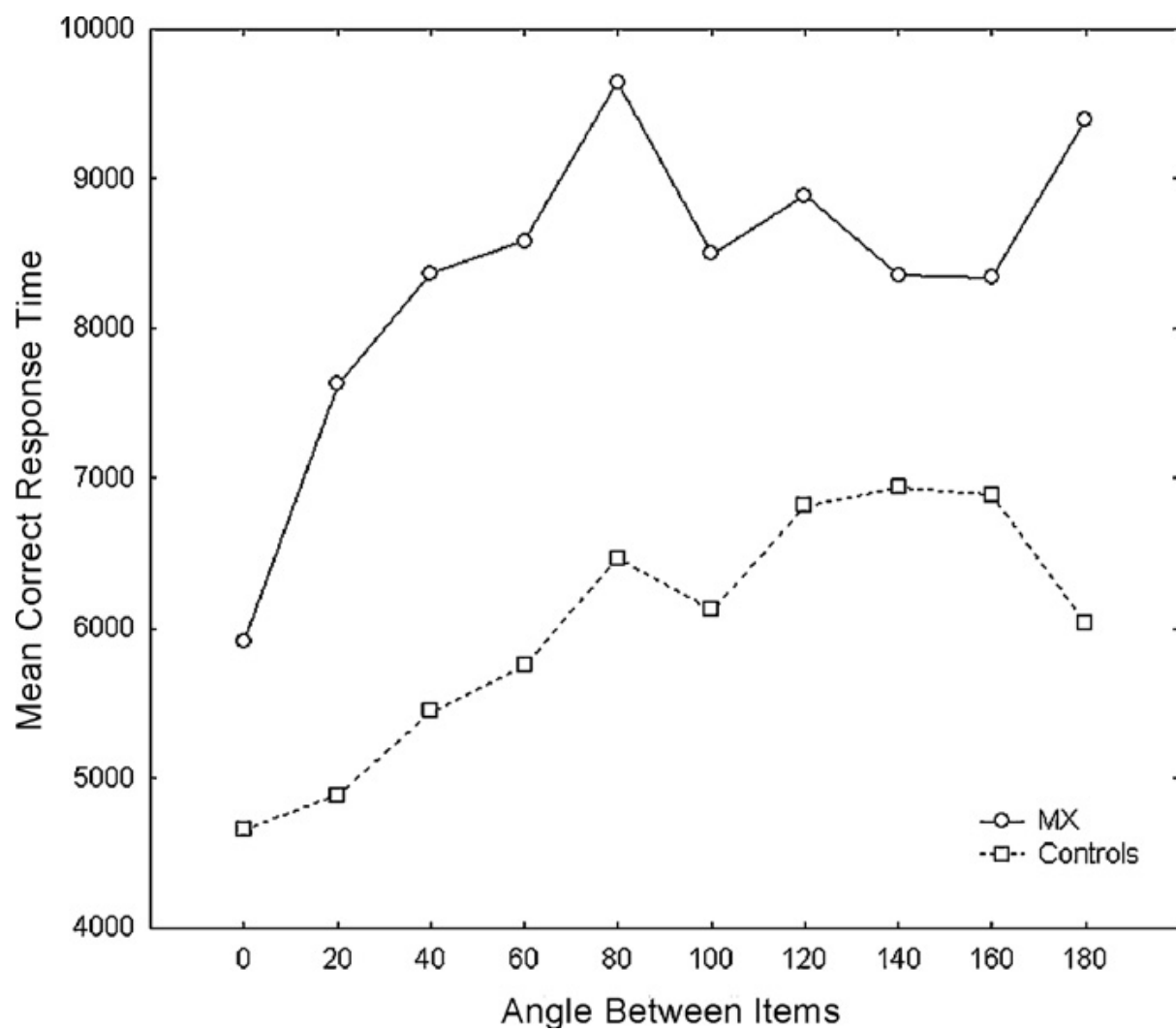


Figure 3

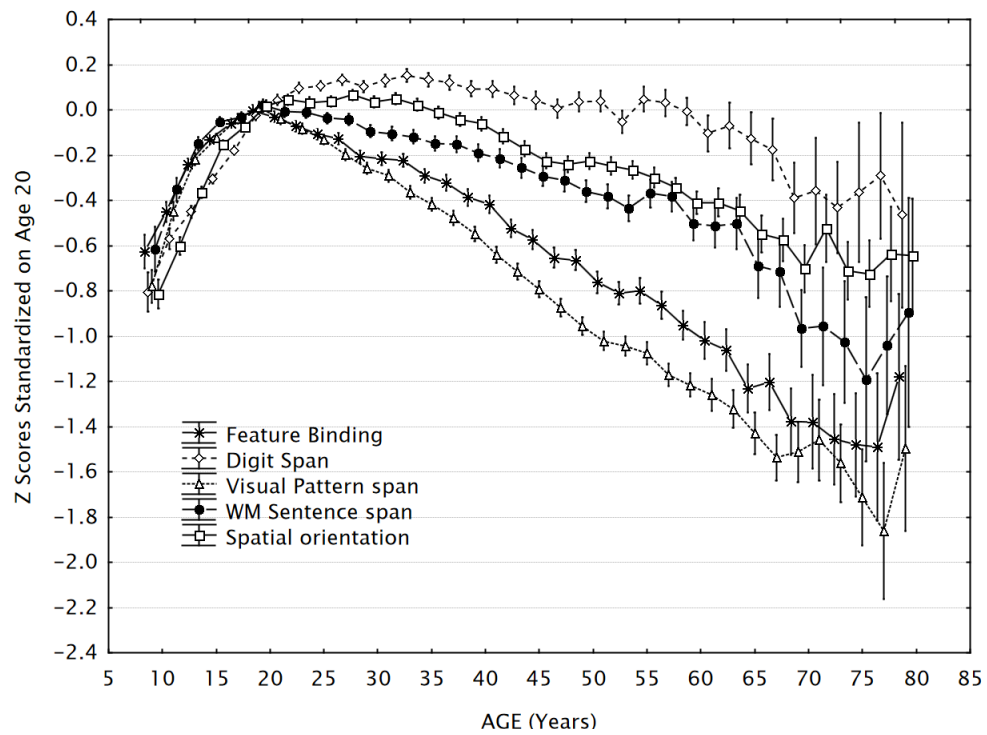


Figure 4

